A Novel Method of Quantifying Changes in Tibiofemoral Joint Stability after Ligament Injury via Eigendecomposition Using In Vitro Robotic Testing

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INTRODUCTION: Tears of the anterior cruciate ligament (ACL) and medial collateral ligament (MCL) are among the most common knee injuries and often result in tibiofemoral instability [1,2]. Measures of knee laxity, which describe the joint's uniplanar load-displacement response, have been used extensively to characterize the degree of ligament injury. However, they do not fully capture the joint's coupled, multidirectional stability, which can contribute to misdiagnosis, graft failure, or patient dissatisfaction [3,4]. Complementing these data, eigendecomposition provides a framework to characterize stability by accounting for all directions of loading, and it describes how rapidly the joint will return toward (for a stable system) or move away from (for an unstable system) a given equilibrium pose [5]. Although widely applied in mechanical and electrical systems, eigendecomposition has rarely been used to assess the passive structural behavior of the knee both in its native state and after ligament injury. Thus, the objectives of this study were: 1) to describe an in vitro method for evaluating tibiofemoral stability using eigendecomposition; and 2) to quantify changes in stability following complete sectioning of the ACL and MCL. We hypothesize that eigendecomposition will demonstrate decreased knee stability after ligament sectioning in response to independently applied anterior and valgus loads.

METHODS: Twelve cadaveric right knees (7 females/5 males; mean age = 50 (range 25-65)) were prepared for testing and mounted to a robotic manipulator (ZX165U, Kawasaki) equipped with a six-axis force-torque sensor (Theta, ATI). The method used to quantify stability had four steps: 1) Determine an equilibrium position and orientation (pose) of the tibia relative to the femur that satisfies a target loading condition. Poses for two conditions were determined for each knee: 15° of flexion with an 8 Nm valgus moment and 30° of flexion with a 100 N anterior force. These loading conditions were chosen because they are used clinically to diagnose injury to the MCL and ACL, respectively. 2) At each equilibrium pose, translate and rotate the tibia by 0.3 mm and 0.3°, respectively, along and about each anatomical axis other than flexion/extension in both positive and negative anatomical directions. 3) During each perturbation, record the change in reaction forces and moments in all directions. The outputs of each perturbation are used to construct a 5-by-5 matrix of the linearized stiffness response (comprised of 25 unique stiffness terms). 4) Calculate the eigenvalues $\lambda_1, \ldots, \lambda_5$ of each stiffness matrix. The knee is stable if and only if the real parts of all eigenvalues are negative; thus, the maximum real (i.e., least stable) eigenvalue was used to test our hypothesis. Importantly, the magnitudes of the eigenvalues quantify how rapidly the joint returns toward equilibrium; as such, a smaller magnitude negative eigenvalue represents decreased stability. After testing the intact state, the ACL was sectioned in six knees (Cohort 1), and the MCL was sectioned in the other six knees (Cohort 2). Steps 2-4 were repeated at the previously determined equilibrium poses to quantify the change in stability caused by ligament sectioning. Median and range of the maximum real eigenvalue are reported. To test our hypothesis, the maximum real eigenvalues in the sectioned state were compared to the intact state via paired t-tests for both loading conditions (α=0.05).

RESULTS: The maximum real eigenvalue was negative for all knees and conditions tested (Figure 1). After MCL sectioning, the median maximum real eigenvalue increased by 3.6 in the valgus loaded pose (p=0.02) and by 4.5 in the anterior loaded pose (p<0.001) After ACL sectioning, the median maximum real eigenvalue increased by 7.8 under valgus moment (p=0.01) and by 11.8 under anterior force (p=0.003).

DISCUSSION: Our hypothesis that sectioning the ACL and MCL would decrease stability in response to valgus and anterior loading conditions was supported. The inter-specimen variability in the effect of ligament sectioning was large; some knees had a large decrease in eigenvalue magnitude, indicating the joint returned to its equilibrium pose much more slowly, while others had minimal changes. This was especially true for the loads applied in each ligament's non-primary loading direction (valgus moment for the ACL, anterior force for MCL). The range of changes in stability after sectioning are likely related to variations in local articular anatomy at the equilibrium point and intersubject variability in ligament slacks. Further analysis of the eigenvectors associated with the maximum eigenvalues will identify the directions of least stability in each condition based on the ACL and MCL's complementary roles in response to both anterior and valgus loads. This approach, when combined with conventional laxity measures, may help identify loading directions most sensitive to ligament injury to improve injury diagnosis and identifying the surgical or rehabilitation strategy that best restores stability. Eigendecomposition is limited by linearization to a small region around an equilibrium point; however, it provides a framework for developing control strategies to maintain stability within that region where the linear approximation is accurate [5].

SIGNIFICANCE/CLINICAL RELEVANCE: Eigendecomposition provides a rigorous framework for characterizing knee stability and complements tests of knee laxity. The approach may be used to develop diagnostic tools and guide surgical and rehabilitation strategies to restore stability after ligament injury.

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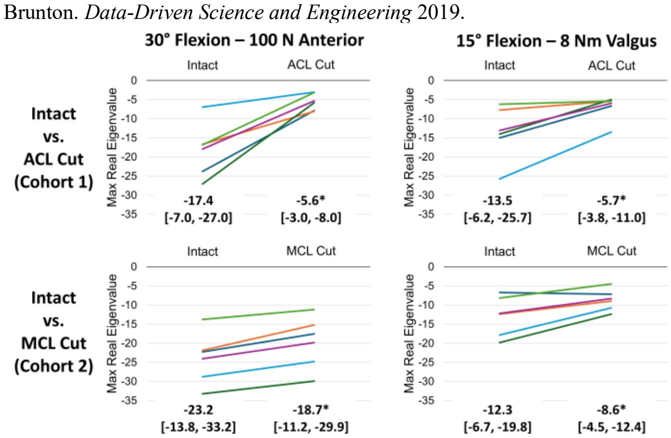

Figure 1. The maximum real eigenvalue of 12 cadaveric knees split into two cohorts (n=6 each) in the intact and ACL- and MCL-sectioned states under two loading conditions: 100N anterior force at 30° of flexion (left), 8Nm valgus moment at 15° of flexion (right). Median and range are reported for each condition and state, * indicates p<0.05 for sectioned state relative to the intact state.